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Thermal fields in grain during storage – their sources and effects on silo structure reliability[1,2]

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A b s t r a c t. Particulate organic materials stored in silos are influenced significantly by the thermal and moisture fields within the stored materials. These man-made ecological systems can be subjected to different kinds of actions and influences which can affect either the stored agromaterial and/or the silo structure. These thermal effects depend on numerous factors, like the type of stored material, the geometry of the silo (height and diameter), and also the climate and weather conditions during storage.

An overview of the literature associated with the thermal effects on granular agromaterials stored in reinforced concrete silo bins is presented in this paper. This discussion focuses on the environmental influences of these effects.

Results of experimental work conducted in model and full-scale grain elevators located in Poland are presented. Temperature distributions throughout the walls during both the summer and winter periods are presented. In addition, thermal strains measured during storage are discussed and compared with the results of numerical estimations of thermal effects. Structural reliability requirements of the silo were estimated to show the effect which thermal forces have on silo structures.

K e y w o r d s: silo, grain, thermal fields, RC structure, numerical analysis

SOURCES OF TEMPERATURE IN THE SILO

On their way from the farm to the market place most agricultural products go through stages involving production, transportation, processing, packaging and preservation. During the preservation or storage phase, granular products are subjected to several biotic and abiotic influences such as temperature changes coupled with moisture migration. Temperature fields acting within the silo not only influence the quality of the stored product but are also one of the most important factors influencing the reliability of the bulk solid and silo structure.

The sources of temperature changes within a silo storing agricultural bulk solids are influenced by numerous factors, *ie* type of stored material, moisture content, silo shape and geometry (height and diameter), construction materials, and the climate and weather conditions during storage. Temperature changes in stored grain are affected by both external and internal factors. External factors are those associated with ambient daily and/or seasonal air temperature fluctuations. Internal factors are biological and biochemical reactions caused by either insect activity or mould growth resulting from improper storage of the product.

Temperature and moisture are two of the most important factors affecting the quality of granular products stored in silos. These factors primarily influence the presence and distribution of insects and fungi within the stored material, which can cause deterioration of the product. Most of the processes by which agricultural products deteriorate are exothermic. Therefore, it is possible to observe ‘self-heating’ during the deterioration of grain which can produce local increases in the temperature of the stored product up to 80°C.

Temperature fields in bins can also cause failure or even collapse of silo structures. Bartali and Hatfield (1990) suggested that the collapse of a steel storage silo located in the USA was the result of a drop in ambient temperature by over 4°C per day accompanied by already low temperatures (t_e = 9°C).

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In this paper the temperature distribution in model and full-scale silo structures was discussed in addition to the thermal effects caused by temperature changes. Computer simulation models, taking into account the real thermal properties of the system, were also used to model the effects which temperature variations had on structural reliability.

STUDIES ON TEMPERATURE DISTRIBUTION INSIDE THE SILO

In the storage of granular materials both the temperature field distribution within the stored material and the thermal strain field within the structure itself must be considered. The temperature field distribution of the granular materials stored in silos are influenced by many different factors, such as the heat transfer characteristics of the stored material, the heat transfer characteristics of the silo construction materials, the size and geometry of the structures itself, the external ambient air temperatures and the initial grain temperature. The thermal strain field acting on the structure is also affected by the same factors. However, changes in the daily air temperature can effect each of these thermal fields differently. Significant short term daily air temperature changes can have a much larger effects on the thermal strains in the silo while having very little or no effect on the temperature field distribution within the stored material.

Very few studies are available in the literature associated with the effect of temperature on silos during storage. The results of 'in-situ' temperature investigations in full-scale silos were presented *eg* by Blight (1990) and Łapko and Prusiel (1998), however, those silos stored clinker (inorganic materials) rather than agricultural granular materials. Sinha and Wallace (1997) presented long-term temperature field patterns (seasonal ambient temperature changes) in steel silos storing rapeseed. Based on four years of observation, they found that during the summer period temperatures within the grain at the bulk centre were low whereas the outside air temperature was high. Conversely, the reverse situation occurred during winter when the wall temperature outside the silo was low while the grain temperature at the centre of the bulk was high (Table 1).

Short term temperature distributions in cylindrical silos have been studied over the last few years by a research team at Bialystok Technical University (Łapko and Prusiel, 1998; 2001; 2003). Temperature distributions across the walls of grain silos were measured during both heating and cooling phases. Temperatures were measured in concrete grain silos 8 m in diameter and 29 m in height which had a wall thickness of 0.2 m. Temperature probes 200 mm long were used which were able to simultaneously measure temperatures at five evenly spaced points along the probe. The two extreme measuring points on the probe measured the temperature of the contact surface of the concrete wall and the temperature of the grain stored in the silo. Selected diagrams of the temperature distribution within the concrete silo wall thickness, during both increases (heating phase) and decreases in air temperature (cooling phase), are shown in Fig. 1.

What can be clearly seen in Fig. 1 is the non-linear distribution of temperature within the concrete wall thickness during daily increased ambient air temperature (Fig. 1a) and also during nightly dropping ambient air temperature (Fig. 1b). Due to concrete wall thermal inertia, temperature difference at outer silo wall surface in the heating phase was equal to +19.5°C, whereas at inner wall surface (in contact with the grain) the temperature difference was equal to +5.4°C only.

A theoretical model of the thermal fields within the grain in the silo and within the silo wall can be developed based on heat transfer principles. For short term axi-symmetric thermal fields (assuming no moisture effects) the following linear differential equation of heat transfer can be considered:

$$\frac{\partial t}{\partial \tau} = a\left(\frac{\partial^2 t}{\partial r^2} + \frac{1}{r}\frac{\partial t}{\partial r}\right). \quad (1)$$

The equation is written in cylindrical coordinates, where: t – temperature at any point within the silo (°C), r – radial distance from the axis of symmetry of the bin (m), τ – time coordinate (h), and $\alpha = \lambda / (c\rho)$, where: a – coefficient of thermal diffusivity, λ – thermal conductivity, c – specific heat, ρ – material density.

Table 1. Temperature distribution in steel silo for rapeseed (Sinha and Wallace, 1997)

Period	Summer temperature		Winter temperature	
	Wall temperature	Bulk centre temperature	Wall temperature	Bulk centre temperature
1st year	August + 37°C	August + 27°C	December - 7°C	December + 27°C
2nd year	July + 31°C	July + 5°C	January - 16°C	January + 16°C

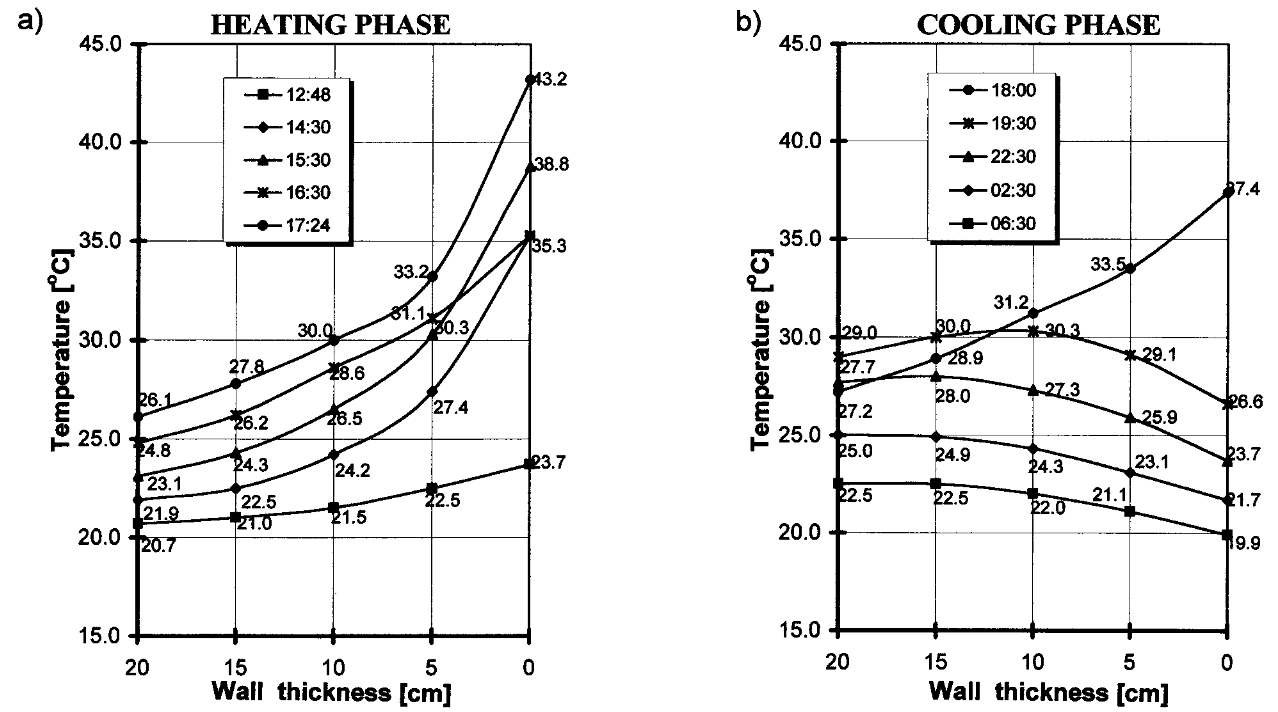

Fig. 1. Short time temperature changes across the concrete wall thickness of grain silo bin during heating and cooling of silo wall induced by daily temperature variations (Łapko and Prusiel, 1998).

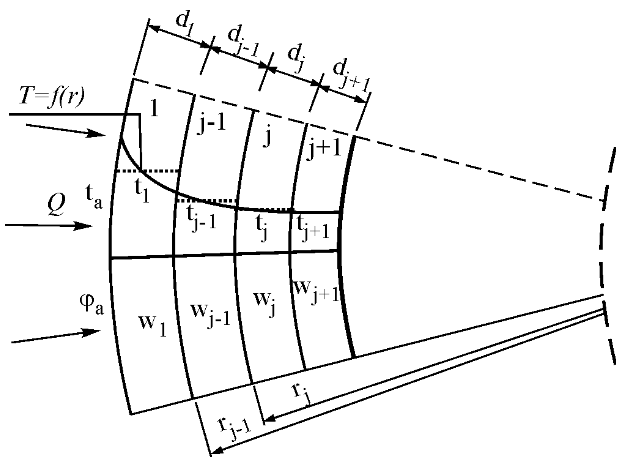

Fig. 2. Assumptions for the analysis of unsteady axi-symmetric heat flow coupled with moisture migration in cylindrical co-ordinates.

For long term storage, the temperature fields within the storage silo must be coupled with the effects of moisture migration, making the problem much more complex. The descriptive model of heat flow coupled with moisture migration in a cylindrical silo is shown in Fig. 2.

To consider moisture effects on silo walls and within the bulk solid system additional differential equations must be included in the analysis which involve moisture transfer within the material:

$$\frac{\partial e}{\partial \tau} = \frac{\mu E_t}{\xi_0 \rho}\left(\frac{\partial^2 e}{\partial r^2} + \frac{1}{r}\frac{\partial e}{\partial r}\right), \tag{2}$$

where: e – vapour pressure (Pa); μ – coefficient of vapour permeability, g m^{-1} h^{-1} Pa^{-1}; E_t – maximum vapour pressure at temperature t (Pa); ξ_0 - water vapour capacity (g kg^{-1}).

Water vapour capacity depends on relative air humidity in pores and can be predicted by differentiation of the isotherm of sorption:

$$\xi_0 = \frac{d\omega}{d\varphi} 1000, \tag{3}$$

where: ω – sorptive humidity (by weight) of the stored material (%); $\varphi = 100e/E_t$ – relative humidity within the pores of the granular material (%).

The analytical solution of the system of Eqs (1), (2) and (3) is very complex. Therefore, the application of approximate methods is usually applied, for instance Jenkyn (1994) and Blight *et al.* (1997) applied the Finite Difference method, while Bala (1991) used the Finite Element method.

In solving numerically these equations, three elementary cases of heat transfer must be considered:

– those associated with the surrounding air and outer surface of the silo wall,
– those between the homogeneous layers (concrete wall or bulk solid),
– those between elementary layers on the boundary between the concrete and bulk solid.

Figure 3 shows a numerical simulation of the effects of short term temperature changes on a granular material stored in a silo. The reinforced concrete cylindrical silo was assumed to have a wall thickness of 20 cm and a silo diameter of 8 m. In this analysis the wheat was assumed to have an initial temperature of 15°C and the silo was subjected to winter time air temperatures.

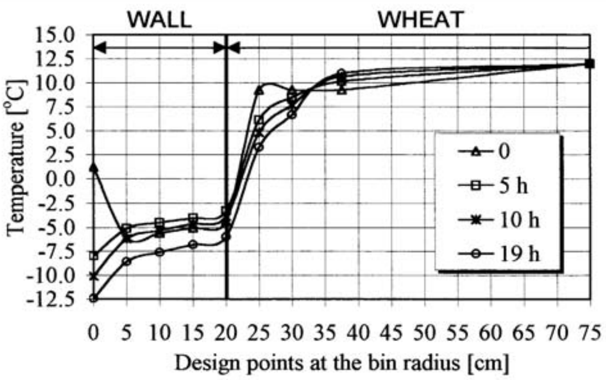

Fig. 3. Temperature changes predicted numerically along the silo bin radius during one day long phase of dropping winter temperature (Łapko and Prusiel, 2003).

Temperature diagrams in Fig. 3 computed on the basis of Eq. (1) clearly show that independently of the significant drop of outer wall temperature the grain in the silo bin remains at constant temperature (excluding a thin layer of grain in contact with the silo wall).

THERMAL INFLUENCES ON SILO STRUCTURE RELIABILITY

Thermal effects not only affect the quality of the stored product but also the integrity of the structure in which the materials are stored. Eurocode 1, prEN 1991-4 (2003), strongly emphasizes that thermal effects must be taken into account when designing silo structures. For evaluation of temperature distribution within the silo wall, the relevant data from the Eurocode 1, EN 1991-1-5 (2003), may be found.

Thermal effects should be considered if the product stored within a silo has a different temperature from that of the whole or a part of the silo wall. Thus, silos should be designed for the additional pressures that can arise from the thermal expansion or contraction of the structure in the presence of a stiff bulk solid. Designing for the thermal fields in silos should be based on either the data described by EN 1991-1-5, Eurocode 1 (2003) or established based on experimental studies.

The following design situation should be considered in the structural analysis of silos:

– a decrease in ambient temperatures relative to the silo wall temperature and bulk solid,
– filling of the silo with a hot particulate solid,
– differential heating rates between exposed steel members and reinforced concrete,
– restraint of the wall displacements by the silo structure.

Temperature differences between the stored product and silo wall and/or the external environment and the silo structure can produce thermal forces, thermal displacements, bending moments, strains and changes in curvature in the structure. Thermal effects on cylindrical silo bins can be classified as:

• radial, tangential and vertically oriented stresses caused by a temperature gradient within the concrete wall thickness,

• tangentially (horizontally) oriented stresses caused by thermally induced surcharge pressures during cooling of the silo wall structure,

• vertically oriented stresses caused by temperature differences between the walls of rigidly grouped concrete silo bins.

Thermal stresses induced by a thermal gradient within a cylindrical silo bin of radius r can be computed using linear equations of elasticity. For a condition in which the bin wall is assumed to be a cylindrical ring, the equations for thermal stress, σ, in polar coordinates are:

$$\sigma_r = \frac{\alpha_t E_s}{r^2}\left(\frac{r^2 - a^2}{b^2 - a^2}\int_a^b Trdr - \int_a^b Trdr\right), \qquad (4)$$

$$\sigma_\theta = \frac{\alpha_t E_s}{r^2}\left(\frac{r^2 + a^2}{b^2 - a^2}\int_a^b Trdr + \int_a^b Trdr - Tr^2\right), \qquad (5)$$

where: r, a, b – radius of the wall sections, α_t - coefficient of thermal expansion for the silo wall, E_s – modulus of elasticity of the silo wall material.

Thermal effects caused by the storing of hot solids in a silo should also be taken into consideration according to prEN 1991-4 Eurocode 1 (2003). When a silo is filled with hot solid, the temperature differentials between the silo wall in contact with this solid as well as the effect of the hot atmosphere above the top of the solid surface occur. The effects of such temperature differentials on the thermal expansion of the silo walls at different levels within the structure should be considered. In addition, bending moments which arise from these thermal differences can be estimated from Eqs (4) and (5).

A reduction in the ambient air temperature induces additional thermal pressures horizontally in the grain mass. This phenomenon is thought to be caused by the differential thermal conditions acting externally on the silo wall and the thermally inert grain.

A decrease in the wall temperature in cylindrical silos can also cause a thermal pressure to act on the vertical walls of the silo. According to prEN 1991-4 Eurocode 1 (2003), thermal pressures, P_{hT} can be computed from the simple formula developed by Andersen (1992):

$$P_{hT} = C_T \alpha_w \Delta T \frac{E_w}{\left[\frac{r}{t} + \frac{(1-v)E_w}{E_{sU}}\right]}, \qquad (6)$$

where: C_T – temperature load multiplier, defined based on the need for silo reliability, α_w – coefficient of thermal expansion of the silo wall, T – temperature differential (drop in mean wall temperature), r – silo radius, t – silo wall thickness, E_w – modulus of elasticity of the silo wall material, E_{sU} – effective elastic modulus of the stored solid during unloading at a given depth, v – Poisson ratio of the stored solid.

Particularly large stress states can occur in the walls of a grain silo when exothermic biochemical processes develop in the stored grain. In this case, an additive effect occurs in which an ambient air temperature drop coupled with a rise in temperature of the bulk solids en masse increases the effects of thermal influences on the stresses in silos. For this case, the formula proposed by Jakovlev *et al.* (1982) can be written as follows:

$$P_{hT} = C_T \frac{(\alpha_w \Delta T_w + \alpha_g \Delta T_g)E_w}{\left[\frac{r}{t} + \frac{(1-v)E_w}{E_{sU}}\right]}, \qquad (7)$$

where: α_g - coefficient of thermal expansion of the grain, ΔT_g – temperature increase in the grain caused by self-heating of the grain.

According to Jakovlev *et al.* (1982), the coefficient of thermal expansion of grain is five times larger than the coefficient of thermal expansion of a concrete wall. During self-

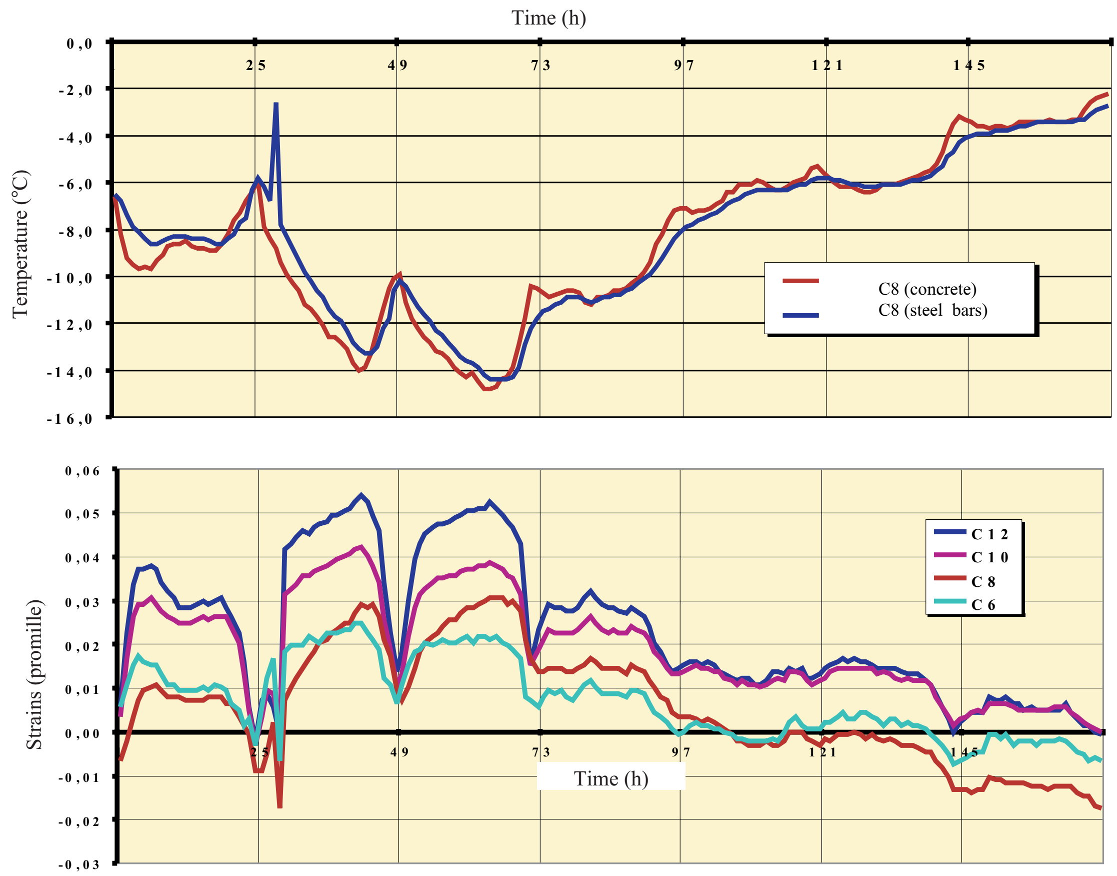

Fig. 4. Selected diagrams of silo wall temperature registered in winter 2002/2003 during 7 day period of monitoring (Łapko and Kołłątaj, 2003) – concrete silo for grain ‘in situ’.

heating of grain, large temperature differentials can occur in the grain over a very short period of time. Based on studies done in Canada (Muir *et al*., 1989), temperature differentials during self heating can reach 50°C with peak temperatures in the grain reaching 65°C within only a few days.

Equations (6) and (7) were developed many years ago and are based on many simplifying assumptions. Therefore, studies were undertaken at Białystok Technical University to determine the thermal effects of silo structures subjected to rapid drops in ambient air temperature. Thermal strains and wall temperatures were monitored in a cylindrical reinforced concrete grain storage silo located in Białystok, Poland, using a telemetric system of measurements (Łapko and Kołłątaj, 2003). The silo had a radius of 4 m and was 29.5 m tall with a wall thickness of 0.2 m. Strains in the hoop reinforcement and external wall temperatures were measured simultaneously at points located on opposite sides of the silo at four different heights. Temperature measurements were taken within a zone located on the southwestern side of the silo and within a zone on the north side of the silo. These two locations represent thermal zones over the silo wall which are: (a) exposed to the sun throughout most of the day, and b) fully shaded throughout much of the day, respectively.

Temperatures and thermal hoop reinforcement strains were monitored during the winter of 2002 and the spring of 2003.

Figure 4 shows selected diagrams of silo wall temperatures during a one-week period. Based on this study it was determined that during periods of storing bulk solids the diagrams of temperature and thermal strains were mutually reciprocal. When the silo was exposed to the sun, rapid changes in the lateral thermal strain and stresses were observed in the silo wall because of the thermal gradient throughout the wall thickness. These studies confirmed the existence of thermal pressures in silos that may have a significant influence on silo bin structure reliability.

CONCLUSIONS

1. In silos storing agricultural products such as grain, it is necessary to precisely predict the temperature fields which can occur in the stored mass and in the silo bin structure.

2. Thermal actions can have a significant effect on silo structure reliability, and in some cases can cause serious damage to the structure, when the temperature distribution in the system is not correctly evaluated.

3. prEN 1991-4 Eurocode 1 (2003) provides provisions concerning the thermal effects in silo structures which designers can use to calculate the thermal actions in silos, however, these methods are based on many simplifying assumptions. For a more exact estimate of the thermal effects in silos 'in-situ' studies are needed to determine the real behaviour of the silo subjected to coupled mechanical and thermal actions.

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